3-D analysis of magnetic stimulation to human cranium

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1 Introduction

Magnetic stimulation is a useful tool for the nerve stimulation because of its non-invasive and painless characters. It is, however, difficult localize a stimulating point because the induced current is wide spread compared to electric stimulation. It is the disadvantage of the magnetic stimulation.

In order to apply magnetic stimulation to a human body effectively, it is very important to investigate how the stimulation occurs in a human body, especially in a brain, from a point of engineering and medical view. Several homogeneous nerve models applied for magnetic stimulation have been proposed [1-4]. From these models, it is considered that the negative space differentiation of the electric field induced by magnetic stimulation, which is called the virtual cathode, is the main factor of depolarization the nerve fiber. The point of its maximum absolute value is known as the maximum stimulating point. Using an inhomogeneous volume conductor, Liu and Ueno proposed that when induced current flowed from a low conductivity volume conductor to a high conductivity one, the virtual cathode appeared at the interface [5].

In this study, we carried out 3-D analysis to calculate distribution of the electric field induced in a homogeneous volume conductor as the first step. In the second step, we constructed a new detailed human cranial model which was divided into 5 areas (skin, bone, muscle, eye and brain) and calculated the eddy current, electric field and virtual cathode after the model was stimulated with an 8-figure coil. In this model, each area was assumed to have different conductivity.

2 Comparison of experimental and analytical results of homogeneous volume conductor

2.1 Methods

Figure 1 shows the magnetic stimulator and stimulating coil (DIA MEDICAL SYSTEM Inc.) used in this experiment. Our experimental model is shown in Fig. 2. The model was a homogeneous volume conductor and its conductivity was as same as that of physiological saline solution (1.6[S/m]). Stimulating coil was a single coil, placed at the bottom of the model. We measured and calculated the electric field (E(X), E(Y), E(Z) and E(X,Y,Z)) induced in the model. The measurement and calculating plane was 1[cm] from the bottom of the model and divided into 1[cm]×1[cm] grids. The measurement points were the corners in each grid

Magnetic Stimulator
(DPS-5010)
DIA MEDICAL SYSTEM Inc.

Stimulating Coil

Power Source
Applied Voltage : 350 [V]
Capacitance : 4.7 [mF]
Wave Form : Pulse Wave
(Width : 30 [μs])
Coil Current : 1020 [A]

Stimulating Coil
Inner Diameter : 25 [mm]
Outer Diameter : 110 [mm]
Height : 6 [mm]
Number of Turns : 13 [Turns]
Resistance : 2.4 [mΩ]
Inductance : 10 [μH]

Figure 1: *The magnetic stimulator and stimulating coil.*

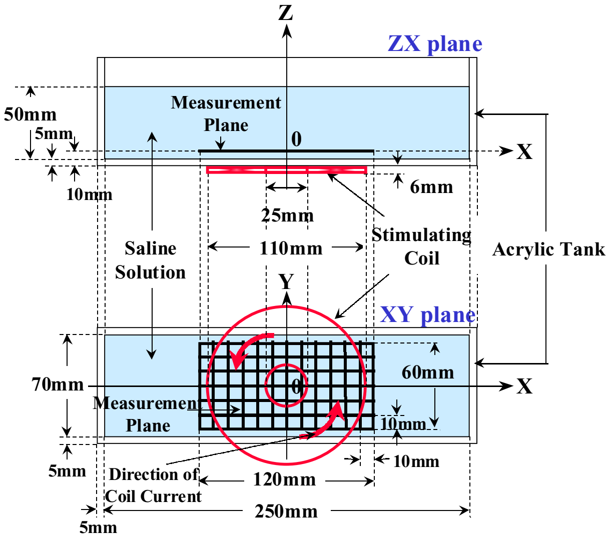


Figure 2: *Homogeneous volume conductor.*

(7× 13=91[points]). We used a program for time dependent electromagnetic fields, OPERA-3d (VECTOR FIELDS Inc.) for numerical analysis. It is based on a finite element method. In the analysis, we computed the coil current from circuit analysis of a magnetic stimulator. We carried out the measurement in Kagoshima University and compared the experimental results with the analytical ones.

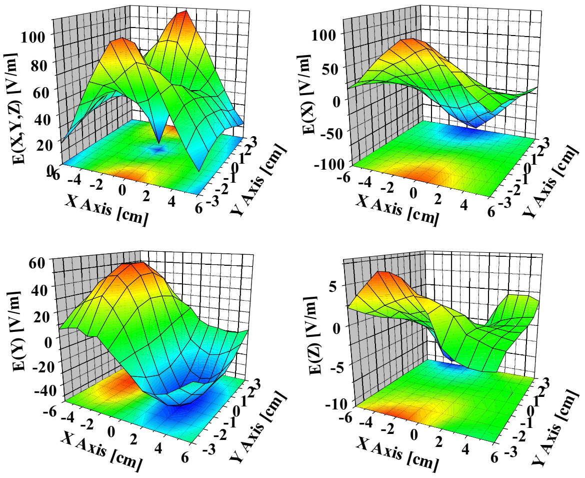


Figure 3: *Experimental results for homogeneous volume conductor.*

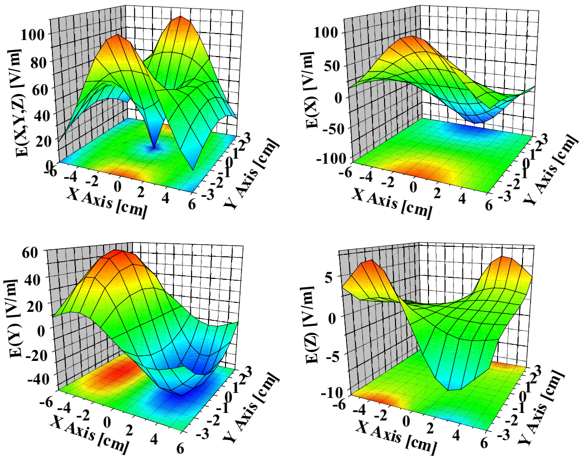


Figure 4: *Analytical results for homogeneous volume conductor.*

2.2 Results

Figures 3 and 4 show the experimental results and the analytical ones, respectively. Both results indicate the electric fields (E(X,Y,Z), E(X), E(Y) and E(Z)) as 3-D contour maps. From the experimental results, E(X,Y,Z) and E(X) exhibited the maximum value at the points of Y=3[cm] and -3[cm], and these values were 2 to 10 times larger than these of E(Y) and E(Z). The analytical results were in good agreement with the experimental ones.

2.3 Discussion

Electric fields of E(X,Y,Z) and E(X) appeared the maximum value at the points of Y=3[cm] and -3[cm] because the coil radius was longer than the tank model of Y direction, thus induced electric field did not expand uniformly.

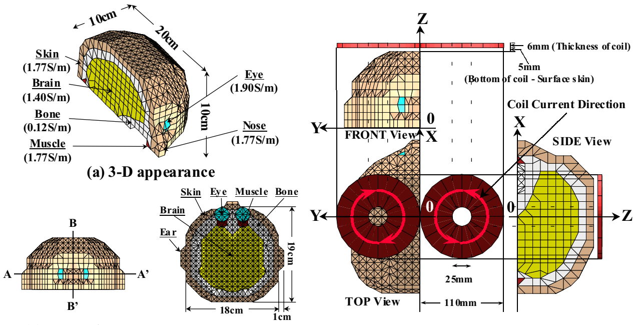
Both results were in good agreement. We concluded 3-D analysis was reliable for the magnetic stimulation.

3 3-D analysis of magnetic stimulation to human cranium

3.1 Human cranial model

As the second stage, we constructed a new detailed model shown in Figure 5 to simulate a human cranium. This real model was divided into 5 areas (skin, bone, muscle, eye and brain) and each area was assumed to have different conductivity. Fig. 5(d) shows a 2-D appearance of the real model with an 8-figure coil. The stimulating coil was the 8-figure coil whose single coil had the same parameters of DPS-5010 in Fig. 1. Fig.

5(e) shows the calculating area (brain). We calculated the eddy current which induced in the models of Fig. 5(a), and the electric field (E(X), E(Y), E(Z)) and the virtual cathode (dE(X)/dX, dE(Y)/dY, dE(Z)/dZ) which appeared in the model of Fig. 5(e), after the model was stimulated with the 8-figure coil.

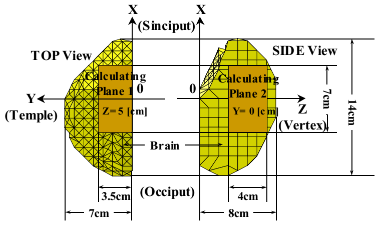


(a) 3-D appearance

(b) Front view

(c) Plane A-A'

(d) 2-D Appearance



(e) Calculating area of the virtual cathode

Figure 5: *Real cranial model.*

3.2 Results of eddy current distributions

Figure 6 shows the results of the eddy current distributions induced in the real model. They were indicated as the contour maps. Figure 7 shows the line drawing of J(X) (the eddy current density along X-axis) from C to C' in Fig. 6(c). The line C-C' exists on the plane A-A' and parallels Y-axis through the point just under the intersection of the 8-figure coil. In Fig. 6, the arrows represent the direction of the eddy current. From the results, the surface eddy current distribution was spread uniformly. However, from the results of the planes A-A' and B-B', the eddy current concentrated on the surface skin and the maximum value appeared at the point just under the intersection of the 8-figure coil. The eddy current was difficult to flow in brain below the bone. From the results of Fig. 7, the eddy current was easy to flow along the bone.

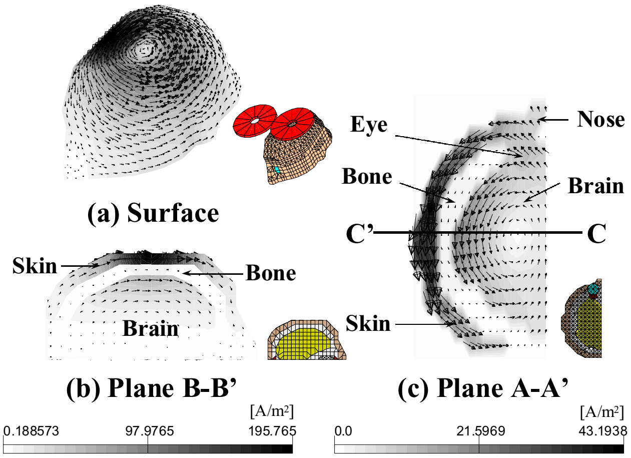


Figure 6: *Results of the eddy current distributions.*

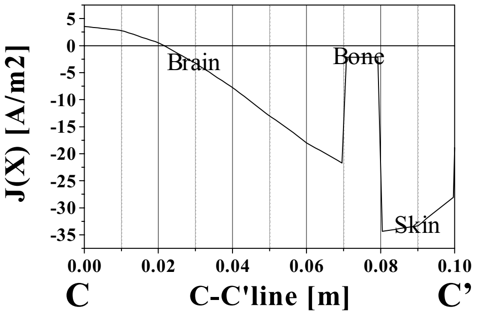


Figure 7: *Eddy current density along X-axis (J(X)) from C to C' in Fig. 6(c).*

3.3 Results of electric field and virtual cathode

Figure 8 shows the results of the electric field and virtual cathode distributions. They were indicated as 3-D counter maps. From the results, E(X) exhibited the maximum value at the point just under the intersection of the 8-figure coil, while E(Y) and E(Z) exhibited the maximum value at the sincipital point of the temple side and at the occipital point of the vertex side, respectively.

About the virtual cathode, dE(X)/dX and dE(Z)/dZ exhibited the minimum value (maximum absolute value) at the sincipital point away from the maximum point of the electric field, while dE(Y)/dY exhibited the minimum value (maximum absolute value) at the occipital side. From Fig. 8(a), the minimum value (maximum absolute value) of dE(Y)/dY was about 2 times larger than that of dE(X)/dX.

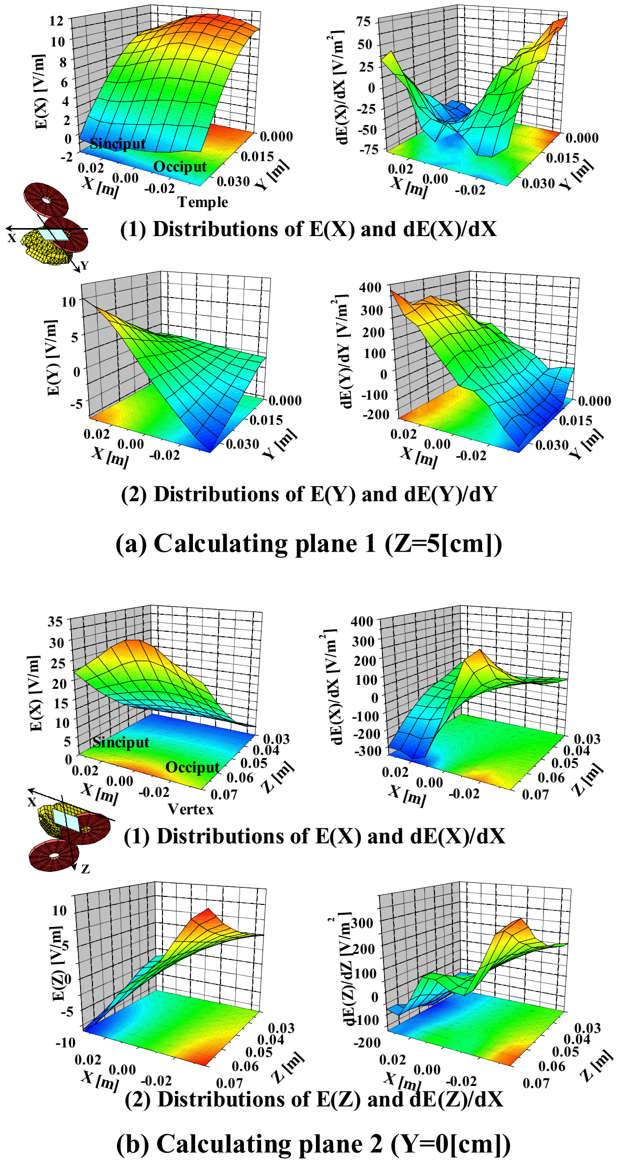


Figure 8: *Results of the electric field and virtual cathode distribution.*

3.4 Discussions

By 3-D analysis using the real cranial model, we calculated more realistic eddy current and virtual cathode distribution in the transcranial magnetic stimulation. According to the calculations, we confirmed that the eddy current induced with magnetic stimulation was influenced by the conductivity and the structure of the model. These results agreed quantitatively with experimental ones, which one of the authors carried out with an acrylic cranial model [6]. The maximum value of virtual cathode along X-axis and Z-axis appeared at the sinciput, but that along Y-axis was located at the occiput. From the results of the virtual cathode in Fig. 8(a), it was suggested that the nerve perpendicular to the coil current direction would stimulate more effectively than the parallel one in the same plane.

4 Conclusions

3-D analysis was useful method for investigate of the magnetic stimulation. By using this method, we could estimated more realistic distributions of the eddy current, electric field and virtual cathode induced in the human cranium with magnetic stimulation. This method is helpful to develop the focal magnetic stimulating coil.

References

1. B.J. Roth and P.J. Basser, “A model of the stimulation of a nerve fiber by electromagnetic induction”, IEEE Trans. Biomed. Eng., Vol. 37, No. 6, pp. 588-597, 1990.
2. P.J. Basser, “Focal magnetic stimulation of an axon”, IEEE Trans. Biomed. Eng., Vol.41, No. 6, pp. 601-606, 1994.
3. S. Ueno, T. Tashiro and K. Harada, “Localized stimulation of neural tissues in the brain by means of a paired configuration of time-varying magnetic fields”, J. Appl. Phys. **64**(10), pp. 5862-5864, 1988.
4. S. Ueno, T. Matsuda and M. Fujiki, “Functional mapping of the human motor cortex obtained by focal and vectorial magnetic stimulation of the brain”, IEEE Trans. Magnetics, Vol. 26, No. 5, pp. 1539-1544, 1990.
5. R. Liu and S. Ueno, “Stimulation of the influence of tissue inhomogeneity on nerve excitation elicited by magnetic”, Proceedings-20th Annual International Conference-IEEE/EMBS, pp. 2998-3000, 1998.
6. K. Yunokuchi, H. Yoshida, K. Mamitsuka and T. Asakura, “Investigation of the distribution of eddy current and nerve excitation in the voluntary volume conductor using the magnetic stimulator”, Trans. IEE of Japan, Vol. 116-C, No. 2, pp. 145-150, 1996.